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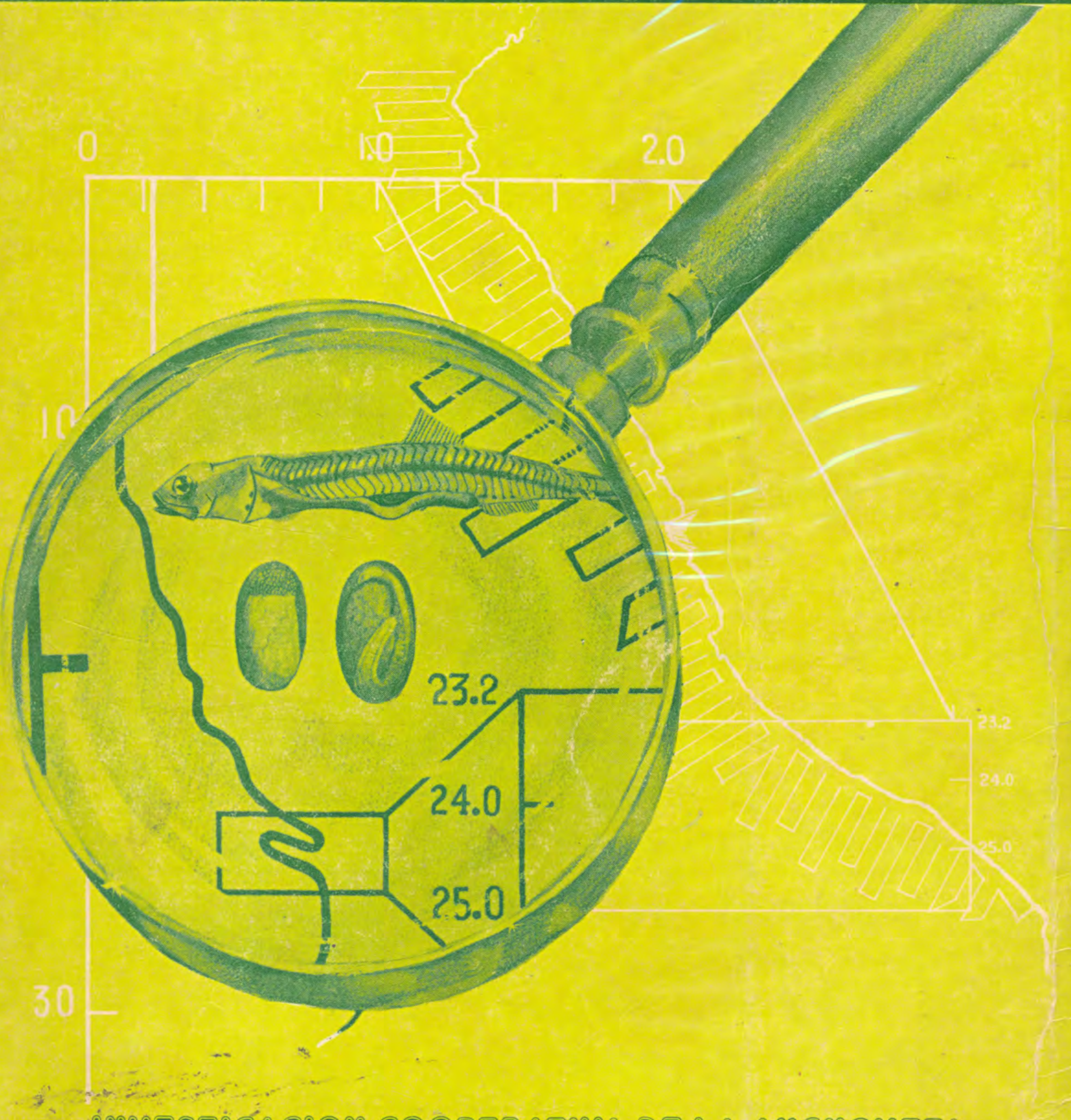

INVESTIGACION COOPERATIVA DE LA ANCHOVETA Y SU ECOSISTEMA-ICANE-ENTRE PERU Y CANADA

CALLAO 1981 PERU

ORGANIC MATTER IN UPWELLING OFF NORTHERN PERU, NOVEMBER 1977

by

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ABSTRACT

The quantity of organic carbon and nitrogen in particulate matter sampled off the coast of northern Peru in November 1977 shows statistically significant correlation with other chemical properties measured in the region at the time. Organic matter concentrations were higher than those measured in other upwelling areas. The greater organic productivity in the upwelling off northern Peru is primarily a consequence of the chemical character of the upwelled water.

RESUMEN

Muestras tomadas fuera de la costa norte del Perú en noviembre de 1977 revelan que la cantidad de carbón orgánico y de nitrógeno particulado se relaciona estadísticamente con otras propiedades químicas medidas en la misma región y tiempo. Las concentraciones de materia orgánica fueron mayores que las de otras áreas de afloramiento. La mayor productividad orgánica de los afloramientos del norte del Perú es en principio una consecuencia de la constitución química del agua aflorada.

INTRODUCTION

Particulate organic matter (POM) constitutes a substantial portion of the suspended matter in much of the ocean. Living material is the major component of it in regions of high primary production. The quantity and nature of organic particulate matter which serves as food within the inshore waters off Peru largely determines the development and survival of juvenile and adult anchoveta (Lasker, 1975, Ware et al., 1979).

The purpose of this paper is to describe the regional and depth distribution of organic matter in coastal waters off northern Peru in November 1977, to relate these to other chemical properties measured at the time and to examine the relationship between POM and the process of upwelling, both off the coast of northern Peru and elsewhere is the ocean.

METHODS

Samples were taken in 12 L PVC Niskin bottles (rinsed daily with 2–propanol to inhibit bacterial growth) during CSS 'Baffin' Cruise 77-030 (Project ICANE) at stations shown in Fig. 1. We tried to obtain at least three samples within the surface mixed layer (indicated by an XBT taken before the bottle cast) and up to four samples below (to 100m).

The total contents of the Niskin bottle, less subsamples for salinity, oxygen, TOC[1] and nutrient determinations (ca. 2 L), were filtered under gravity in a closed system through 0.8 μm silver filters (Sela Flotronics, precombusted at 450°C for two hours) and the filtered volume (2-10 L) measured to 0.01 L. The filters were frozen and analysed ashore one month later in a commercial dry combustion instrument (Hewlett-Packard 185B CHN analyzer) modified as described by Sharp (1974). Filter blanks equivalent to 1 mgC m^{-3} and 0.1 mgN m^{-3}, and a standard deviation of replicates of the same order, imply that a difference between samples of 5 mgC m^{-3} or 0.5 mgN m^{-3} indicates a real difference in the POM [taken as POC +PON (particulate organic nitrogen)] of the water sampled.

Samples for TOC determination were acidified to pH 2 with syrupy phosphoric acid and stored frozen. The determination was performed ashore using the dry combustion method of MacKinnon (1978). Nutrient, chlorophyll a and phaeophytin analyses were performed aboard ship using standard

1/ Total organic carbon (TOC) contains two broad classes: particulate organic carbon (POC), which is that material retained by a filter of specified pore size, and dissolved organic carbon (DOC), which is the filter-passing material.

Table 1. Significant[1] correlations within the surface mixed layer off northern Peru. Data are log. transformed; LONG = distance longshore[2]; OFF = distance offshore; TEMP = temperature; SALT = salinity; DENS = density; OXYG = oxygen; PHOS = phosphate; SILI = silicate; CHLO = chlorophyll; PHAE = phaeophytin.

	LONG	OFF	TEMP	SALT	DENS	OXYG	NO_3	NO_2	PHOS	SILI	CHLO	PHAE	POC	PON
TEMP		0.791												
SALT		0.679	0.571											
DENS		-0.743	-0.987											
OXYG			0.545		-0.534									
NO_3				0.533										
NO_2														
PHOS		-0.490	-0.744		0.738	-0.546								
SILI			-0.651	-0.488	0.619	-0.514		0.542	0.720					
CHLO			-0.512		0.504									
PHAE			-0.518		0.530						0.602			
POC		-0.738	-0.645		0.635									
PON		-0.725	-0.646		0.637								0.994	
C/N														
TOC		-0.544											0.594	0.584

1 For all except TOC, d.f. = 45; for TOC, d.f. = 25; the critical value to be exceeded for a statistically significant correlation is 0.487 ($P < 0.01$, d.f. = 25).

2 Measured normal to a baseline passing through 10°25'S, 79°W and 10°S, 78°11'W, representing rotation of approximately 30°W of true N.

methods (Strickland and Parsons, 1968; Holm-Hansen et al., 1965), oxygen concentrations were determined by a modified Winkler method (Levy et al., 1977), and salinity was determined with an inductive salinometer.

The area investigated off Peru was bounded by 6°30'S, 81°W-8°30'S, 80°30'W-10°30'S, 79°W and the coast, for a total of ca. 40,000 km^2. The total area of our W. African (Senegal) survey was much greater. For purposes of comparison, an equivalent area off Africa, that portion east of 18°W between 12°N and 16°N and the coast, was used in this study.

The intensity of association between all pairs of measured variables was quantified by computation of a product-moment correlation coefficient matrix (Sokal and Rohlf, 1969). This was also computed for waters of the Senegal upweeling area. The data base for POM in this analysis was expanded by the inclusion of unpublished results obtained on the same cruise kindly provided by Dr. Glenn Harrison, MEL.

RESULTS

Over the entire area, there was a shallow surface mixed layer, 10 to 25 m deep, of oxygenated water of low density separated sharply from denser, low-oxygen water below. The mixed layer depth showed no consistent pattern with location but did in fact differ between close stations taken as little as two days apart. There was no statistically significant ($P < 0.01$) change with depth of any measured variable within this layer (Table 1) in contrast to subsurface waters within which temperature, salinity, POC, PON and chlorophyll decreased and density increased, significantly with depth (Table 2). There were, however, other correlations of significance within the surface layer:

(1) Temperature in the surface layer was low (14-19° C) for the latitude and season. It was higher offshore than inshore but did not change significantly longshore (Table 1). Most of our stations fell within the Chimbote-Huarmey 'tongue of cold water' (Zuta et al., 1978).

The absence of significant longshore variation in temperature justifies the inclusion of other stations (e.g. Station 56, off Pimentel) in the data set

(2) Salinity in the surface layer varied over only a small range (34.9 to 35.2°/oo). The surface layer was significantly more saline offshore, but exhibited no significant longshore variation (Table 1). Warmer waters tended to be more saline. The 35.1°/oo isohaline was essentially co-incident with the 19°C isotherm and together they serve to define the offshore limit of the upwelling area (Fig. 1).

(3) In response to the offshore increase in temperature, density decreased from σ_t = 26.0 to σ_t = 25.0 with distance offshore. (Table 1).

(4) Low oxygen concentrations (below 5.0 mL/L) and oxygen undersaturation characterized much of the surface layer. There was significantly more oxygen in warmer, less dense water with a lower phoshpate and silicate content but no significant variation of oxygen concentration **per se** either longshore or offshore (Table 1).

(5) There was significantly more nitrate in more saline watar (Table 1).

(6) Phosphate concentration in the surface layer was enhanced over open-ocean values (above 0.5 m mole m^{-3}). Highest concentrations were closest inshore and lowest values offshore but there was no consistent longshore variation within this layer. Inverse correlation with temperature accounted for 55°/o of the variability of phosphate concentration within the surface mixed layer. There was significantly more phosphate in the coldest, densest, least-oxygenated waters.

(7) Silicate concentration in the surface layer was enhanced over open-ocean values (above 1.5 m mole m^{-3}). Correlation with temperature accounted for 42°/o of the variability in silicate concentration within the surface layer. There was significantly more silicate in the coldest, densest, least-oxygenated waters, also enhanced

Fig. 1. Location of stations off northern Peru, November 1977. Within circle A lie Stations 193 to 213 and within circle B, Station 116. The offshore limit of the upwelling area, as indicated by the 19°C surface isotherm and 35.1°/oo isohaline, lies between Stations 77 and 75, 257 and 124, 315 and 316.

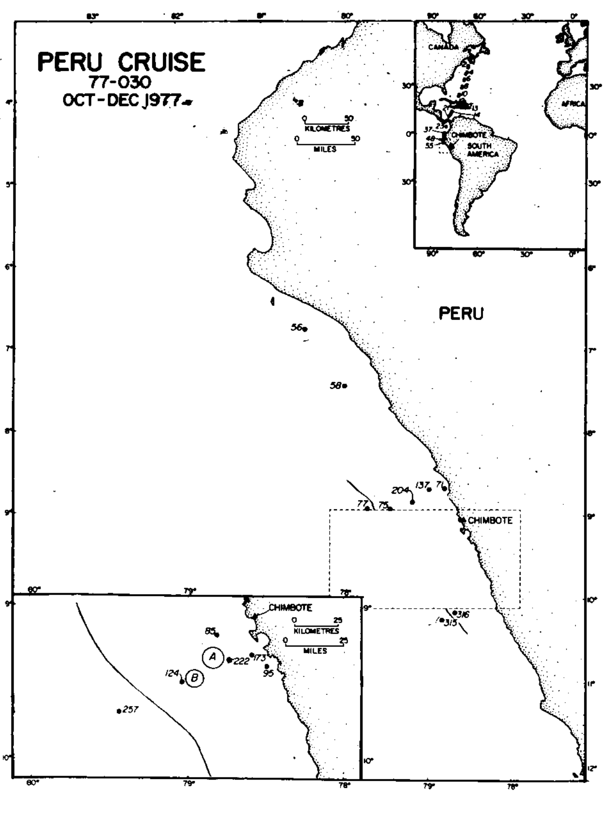


Fig. 2. Distribution of particulate organic carbon within the surface layer. Isopleths are in mg C m^{-3}.

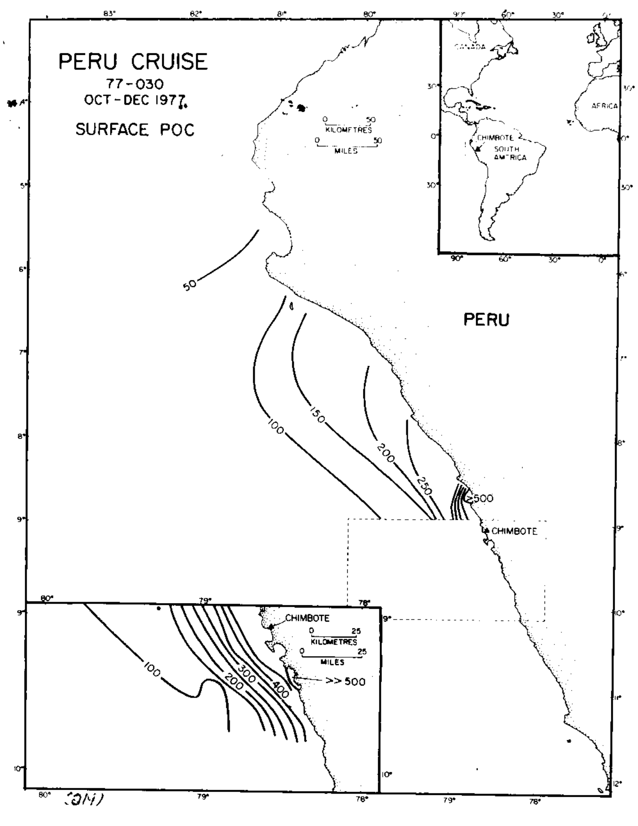


Fig. 3. Distribution of particulate nitrogen within the surface layer. Isopleths are in mg N m^{-3}.

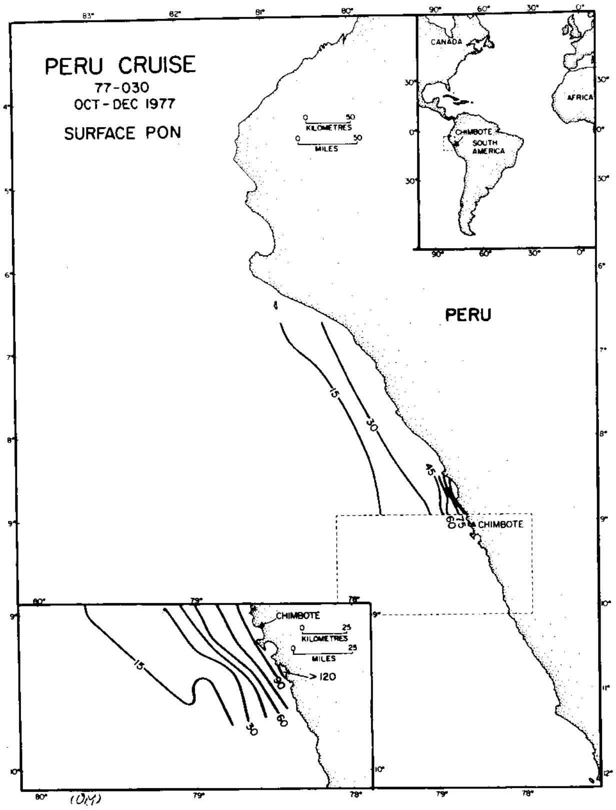
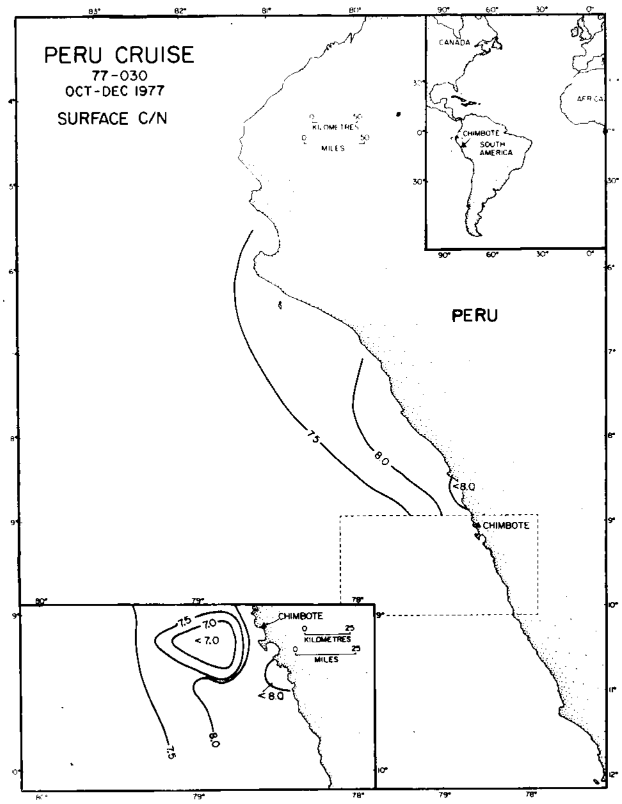


Fig. 4. Distribution of organic carbon to nitrogen atomic ratios in particulate matter within the surface layer off northern Peru, November, 1977.



in nitrite and phosphate.

(8) There was significantly more POC in the surface layer inshore than offshore, but no signficant variation longshore (Fig. 2). The concentration of POC was significantly higher in colder, denser water (Table 1).

(9) The surface layer distribution of PON is similar to that of POC with the highest concentrations closest inshore, lowest offshore, and no longshore variation (Fig. 3). The concentration of PON was significantly greater in colder, denser, water (Table 1).

(10) The ratio of organic carbon to nitrogen in particulate matter (C/N) showed no consistent pattern with location within the surface layer (Fig. 4). This is different from the situation off Senegal, where the C/N ratio increased regularly to open ocean values (above 7.5) from inshore values (below 6.5; Fig. 5). An atomic C/N ratio close to that of phytoplankton (5-6; Parsons, 1975) implies that nutrient limitation is not operative inshore (Walsh, 1977). The waters off Senegal were dominated by diatoms; the waters off northern Peru are characterized by a mixed assemblage of phytoplankton (Belyayeva, 1976; Shushkina **et al.**, 1978; Sorokin, 1978; Sukhanova **et al.**, 1978), which may suffer some restriction of nitrogen (Bates, 1979) where the populations were most dense closest inshore (Platt et al., 1979).

The general picture is of cool, low-salinity water with enhanced phosphate and silicate content upwelling close inshore. This water warms, becomes more saline, and suffers loss of phosphate and organic matter as it moves offshore.

Few POM data are available from earlier studies in the region of intereast. This is surprising as further south it has been intensively studied (Walsh, 1977). Our POC measurements off northern Peru in November 1977, were higher than those made by Mel'nikov (1976) during August 1972 within the same area, but that was an El Niño year (Wooster and Guillen, 1974) and hence likely to yield lower values. Our PON concentrations were lower than those (4.5-185.1 mgN m^{-3}) found by Garfield **et al.** (1976) off central Peru (15-16°S, 75°30'W-76°30'W) in May 1977 but their samples were from the surface only, and their mean is arithmetic. When recalculated as geometric, their mean of 28.8 mgNm^{-3} is more closely comparable with ours (Table 3). Values from oligotrophic regions of the southeast Pacific are ten times lower than in the surface mixed layer off northern Peru (Table 3).

Below the surface mixed layer, within subsurface waters (to 100 m) chemical properties showed similar relationships: there were still no significant changes longhore, but there were significant correlations with distance offshore (Table 2).

(1) The oxygen content increased offshore, while nitrite and ammonia decreased, the last showing a significant inverse correlation with oxygen content, and positive correlation with nitrite.

(2) There was more phosphate in colder, less saline (but denser) water, as was the case within the surface layer. Silicate did not show these correlations.

(3) Both POC and PON decreased offshore, but the C/N ratio showed no consistent change, a reflection of the surface layer pattern. There was less POM (POC and PON) in more-oxygenated water. There was more POM in waters which had higher chlorophyll concentrations. Increasing C/N ratios in the POM were more a consequence of a decreasing proportion of nitrogen in the material than of an increasing proportion of carbon. In waters with a higher POM content, there was more TOC although on average only 16o/o of the TOC in the surface layer was accounted for by POC.

Outside the upwelling area POC, PON, and TOC decreased exponentially with depth within the top 500 m of the water column (correlations with depth, log. transformed data; POC, $r = -0.783$, $n = 31$; PON, $r = -0.830$, $n = 31$; TOC, $r = -0.729$, $n = 30$; $P < 0.01$). The ratio of carbon to nitrogen in the particulate matter increased linearly over the same depth range (C/N, $r = 0.675$, $n = 31$, $P < 0.01$). Within the upwelling area off northern Peru, however, this exponential decrease with depth was less apparent (Table 2). Positive correlation of C/N with oxygen concentration was observed outside the upwelling area (to 500 m), and within the surface layer in the upwelling region.

There were no significant longshore variations in any variable with the possible exception of chlorophyll and phaeophytin which, in a varimax matrix accounting for 82.7 o/o of the total problem variance in the log transformed data (Harmann, 1970) were significantly correlated ($r = 0.708$ and $r = 0.728$, respectively) with a 'longshore factor'. However, the variance of these two measurements exceeded 30o/o of the mean, in violation of the assmuptions upon which this statistic is based. Nitrate concentration increased in the offshore direction in both surface and subsurface layers, whereas POM decreased in this direction. Higher phosphate concentrations were always associated with colder, less saline (though denser) waters. Phosphate and silicate concentrations were highly mutually correlated both within the surface layer and sub-surface; carbon and nitrogen in particulate matter were even more closely correlated. Below

Table 2. Significant[1] correlations within subsurface waters off northern Peru. Data are log. transformed; LONG = distance longshore[2]; OFF = distance offshore; DEPT = depth of sample; TEMP = temperature; SALT = salinity; DENS = density; OXYG = oxygen; PHOS = phosphate; SILI = silicate; CHLO = chlorophyll; PHAE = phaeophytin.

DEPT	LONG	OFF	DEPT	TEMP	SALT	DENS	OXYG	NO_2	NH_3	PHOS	CHLO	PHAE	POC	PON
TEMP			-0.733											
SALT			-0.598	0.823										
DENS			0.707	-0.987	-0.725									
OXYG		0.587												
NO_2		-0.501												
NH_3		-0.705					-0.550	0.558						
PHOS				-0.532	-0.539	0.502								
SILI										0.5 3				
CHLO			-0.507											
PHAE							-0.524				0.876			
POC		-0.633	-0.612				-0.595				0.626	0.531		
PON		-0.642	-0.568				-0.506				0.587		0.979	
C/N													-0.543	-0.701
TOC													0.644	0.655

1 d.f. = 24, r = 0.496, P <0.01

2 Normal to baseline through 10°25'S, 79°W and 10°S, 78°11'W.

Table 3. Representative values of particulate organic carbon and nitrogen and their ratios in the surface mixed layer of different areas of the ocean. All means are geometric. Coefficient of variation, C_v = standard deviation/mean x 100.

Location (months)	Depth Range M	No. of Samples[1]	POC mgm^{-3} mean (range) C_v	PON mgm^{-3} mean (range) C_v	C/N Atoms mean (range)	Data Source
Off Hawaii (all)	0–100	30	17(8–62) 34%	2.5(1.4–3.7) 21%	8.7(6.4–9.2) 9%	Gordon, 1970
S. Pacific, 150°W (Apr–Jun)	0–100	23	21(11–38) 12%	not given	–	Wangersky, 1976
S. Pacific[2], 155°W (Aug–Oct)	0–100	41	25(10–40) 12%	4.0(2.0–7.0) 21%	7.0(6.2–9.1) 5%	Ichikawa and Nishizawa, 1975
Off Senegal (Feb–Mar)	0–30	39	85(38–231) 10%	14.4(6.3–44.6) 18%	6.9(5.7–7.5) 4%	Pocklington and MacKinnon, 1980
Off N. Peru (August)	0–50	11	113(52–301) 9%	not given	–	Mel'nikov, 1976
Off NW Africa (Feb–May)	0–50	245	133(23–390) 14%	23.8(6.0–49.6) 17%	6.5(4.5–9.2) 10%	Barber and Huntsman, 1975 Packard and Dortch, 1975
Off SW Africa (Apr–May)	0–50	18	152(68–864) 15%	26.6(11.0–163.0) 20%	6.7(5.8–7.9) 4%	Hobson, 1971
Off South California[2] (all)	0–60	433	168(50–1000) 15%	29.2(10–200) 22%	6.7(5.8–7.7) 4%	Eppley et al., 1978
Off N Peru (Nov)	0–25	47	240(56–1056) 13%	36.5(7.2–154.4) 21%	7.7(6.5–10.2) 6%	Pocklington, this paper

[1] May be less for PON and C/N. [2] Ranges estimated.

the surface layer, there was no significant correlation of POM with nutrients, though there was a significant positive correlation with chlorophyll. The Si/P ratio, interpreted off NW Africa as indicative of the upwelling of different water masses (Gardner, 1977), was, off northern Peru, uniformly high (**ca.** 8) in sub-surface waters. The presence of high among generally low (**ca.** 3) ratios in the surface layer (e.g., at stations 71, 95 and 173) is best accounted for by the water, which is cold, having recently been upwelled.

DISCUSSION

Representative values of POC, PON and their ratios in the surface mixed layer of different areas of the ocean are given in Table 3. The ranges of POC and PON extend asymmetrically toward higher concentrations. Geometric means, a better measure of central tendency in such cases, are used in subsequent discussion. Particulate organic matter is distributed as a relatively uniform background upon which are superimposed local accumulations of particles (Wangersky, 1979), and by using a measure of central tendency less influenced by a few extreme high values, a better general comparison between areas can be made.

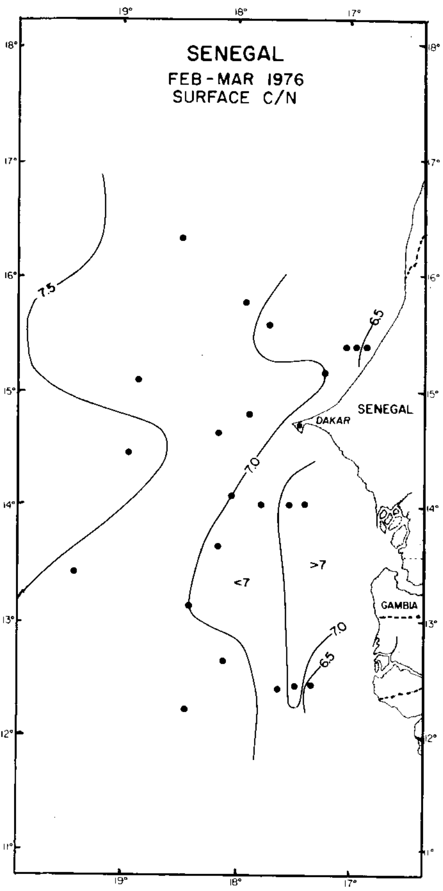
The mean concentrations and ranges of POC and PON (Table 3) follow a sequence that is reasonable in terms of sample origin. The range of mean POC is from 17 to 240 mg C m^{-3} (**cf.** 20 to 200 mg C m^{-3}; Parsons, 1975); open ocean stations have low mean POC (17 to 25 mg C m^{-3}) and upwelling areas higher (85 to 240 mg C m^{-3}). Comparison of means and ranges of representative PON concentrations shows a range of 2.5 to 4.0 mg N m^{-3} in the open Pacific, 14.4 to 36.5 mg N m^{-3} in upwellings.

Quantitatively, the upwelling off northern Peru is distinguished by enhanced concentrations of POC and PON in the surface mixed layer, much higher than in adjacent oceanic waters and higher than in the upwellings off Senegal, northwest and southwest Africa, and southern California. Insofar as POC concentration estimates standing stock (Smetacek and Hendrikson, 1979), this implies a biologically very productive upwelling off northern Peru at the time we were there.

Higher phosphate (x2) and silicate (x3) concentrations in the subsurface waters off northern Peru, as compared with the corresponding source waters off Senegal, represent nutrient enrichment derived from the major water masses of the two regions (Table 4).

From the small amount of wind speed and direction data available to us (Pocklington and MacKinnon, 1980; Zuta **et** al., 1978) it appears that the coastal regions of northern Peru and Senegal do not differ radically in meteorological forcing functions of upwelling. The greater biological production in the upwelling off Peru is initially more a consequence of the chemical character of the upwelled water than of the physical conditions of upwelling: the waters upwelled on the northern Peruvian shelf

Fig. 5. Distribution of organic carbon to nitrogen atom ratios in particulate matter within the surface layer off Senegal and The Gambia, February-March 1976.



being derived from high nutrient eastern south Pacific sub-surface waters (Fig. 6). Examples from other upwelling areas reinforce this point. Nutrient concentrations in the upwelling off northeast Africa (Wyrtki, 1971) are comparable to those off northern Peru but it requires water to be brought from **ca.** 400 m to achieve this (Düing, 1970). In the eastern Caribbean, nutrient enrichment through upwelling is low, because of the relatively impoverished nature of the source waters of the upwelling, and organic production consequently less (Corredor, 1979).

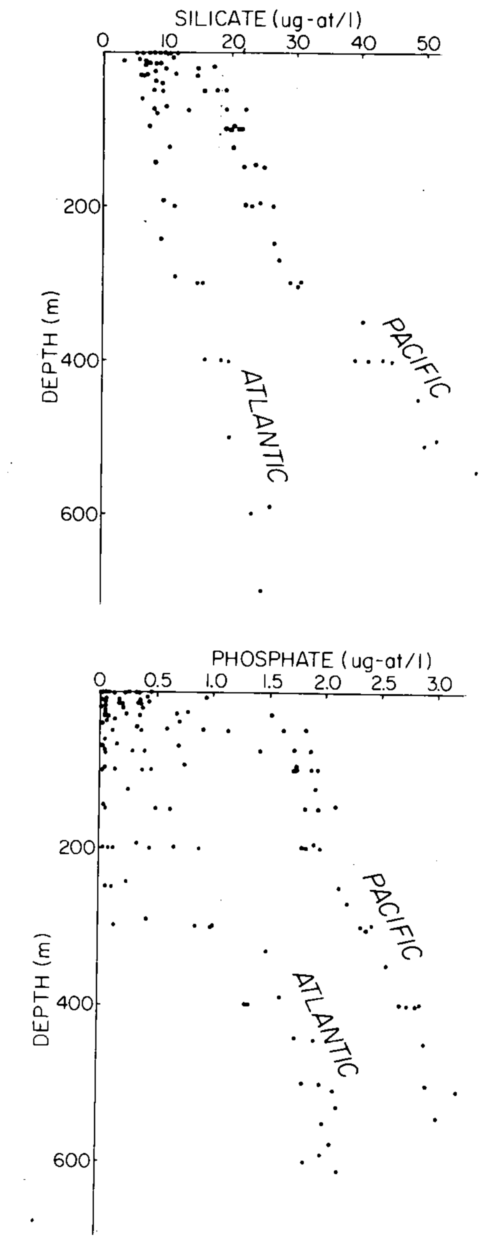
CONCLUSIONS

Two physico-chemical factors which determine the sustained high level of organic production off northern Peru are the high concentration of nutrients in the water which is upwelled, and the persistence of the physical forcing functions. The first is a general feature of the south Pacific Ocean and has probably persisted for as long as there has been a circum-Antarctic circulation (Barker and Burell, 1977). The second feature is much more susceptible to secular variation. Off Senegal, upwelling stops every year, usually in April, when the wind drops and warm low-salinity surface water, which lies west

Table 4. Chemical properties of the source waters of upwelling off northern Peru and Senegal.

Parameter	Peru mean (range)	N	Senegal mean (range)	N
Depth of sample m	40 (20-100)	26	70 (40-100)	32
Temperature °C	14.5 (13.5-16.2)	26	14.8 (13.4-16.7)	29
Salinity °/₀₀	35.01 (34.94-35.09)	26	35.49 (35.37-35.72)	32
Oxygen ml/l	0.35(0.10-1.67)	26	1.73 (1.31-2.96)	31
Phosphate m mole m-3	2.45 (2.06-2.87)	26	1.32 (0.74-1.53)	32
Silicate m mole m-3	23.9 (10.4-45.0)	26	8.1 (4.7-10.8)	26
POC mg m-3	49 (15-151)	26	30(16-48)	25
PON mg m-3	6.6 (1.6-25.8)	26	4.5 (2.3-7.9)	25
C/N	8.6 (6.7-13.8)	26	7.9 (6.8-10.4)	25

Fig. 6. Comparison between the vertical distribution of phosphate and silicate in the north Atlantic and south Pacific Oceans. Units are m mole m^{-3}.



of 23° W throughout the year, reappears over the inshore area. Only because this changeover occurs annually and the warm conditions persist for the major part of the year, is this not recognized as the west African equivalent of El Niño, which is considered to be an exceptional event of irregular occurrence.

The phenomenon known as El Niño should perhaps be viewed not as the incursion of some abnormal water body but as the reestablishment of the surface water conditions that one would normally expect at this latitude. It is the intensive and sustained upwelling off Peru, not its cessation, which is, in a global sense, anomalous.

Note added in proof: Oceanic effects of an 'El Niño' type have been recently reported from the Gulf of Guinea (Hisard, Ph. 1980, **Oceanologica Acta** 3: 69-78).

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